Microsoft

Quantum Computing at Microsoft

Stephen Jordan

math.nist.gov/quantum/zoo

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at stephen.jordan@nist.gov. Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an *n*-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in $\widetilde{O}(n^3)$ time [82,125]. The fastest known classical algorithm for integer factorization is the general number field sieve, which is believed to run in time $2^{\widetilde{O}(n^{1/3})}$. The best rigorously proven upper bound on the classical complexity of factoring is $O(2^{n/4+o(1)})$ via the Pollard-Strassen algorithm [252, 362]. Shor's factoring algorithm breaks RSA public-key encryption and the closely related quantum algorithms for discrete logarithms break the DSA and ECDSA digital signature schemes and the Diffie-Hellman key-exchange protocol. A quantum algorithm even faster than Shor's for the special case of factoring “semiprimes”, which are widely used in cryptography, is given in [271]. If small factors exist, Shor's algorithm can be beaten by a quantum algorithm using Grover search to

Navigation

- Algebraic & Number Theoretic
- Oracular
- Approximation and Simulation
- Acknowledgments
- References

Other Surveys

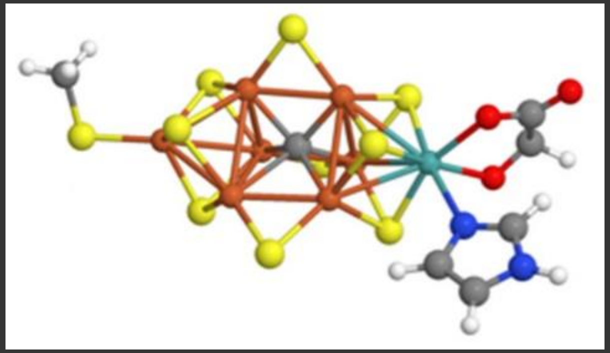
For overviews of quantum algorithms I recommend:

- Nielsen and Chuang
- Childs
- Preskill

- As of November 2018: 60 entries, 392 references
- Major new primitives discovered only every few years.

Simulation is a killer app for quantum computing with a solid theoretical foundation.

Chemistry



Materials

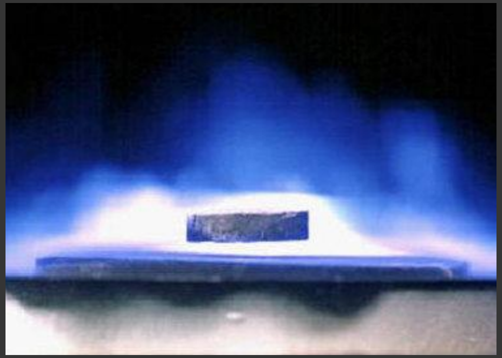


Image: David Parker, U. Birmingham

Nuclear and Particle Physics

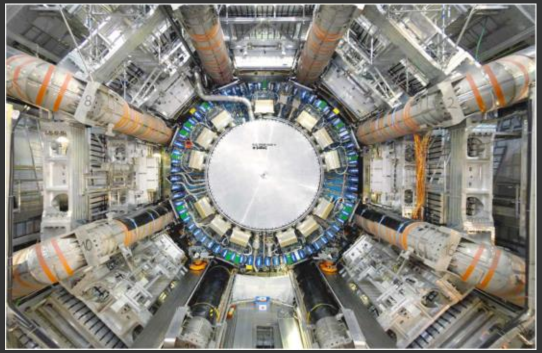
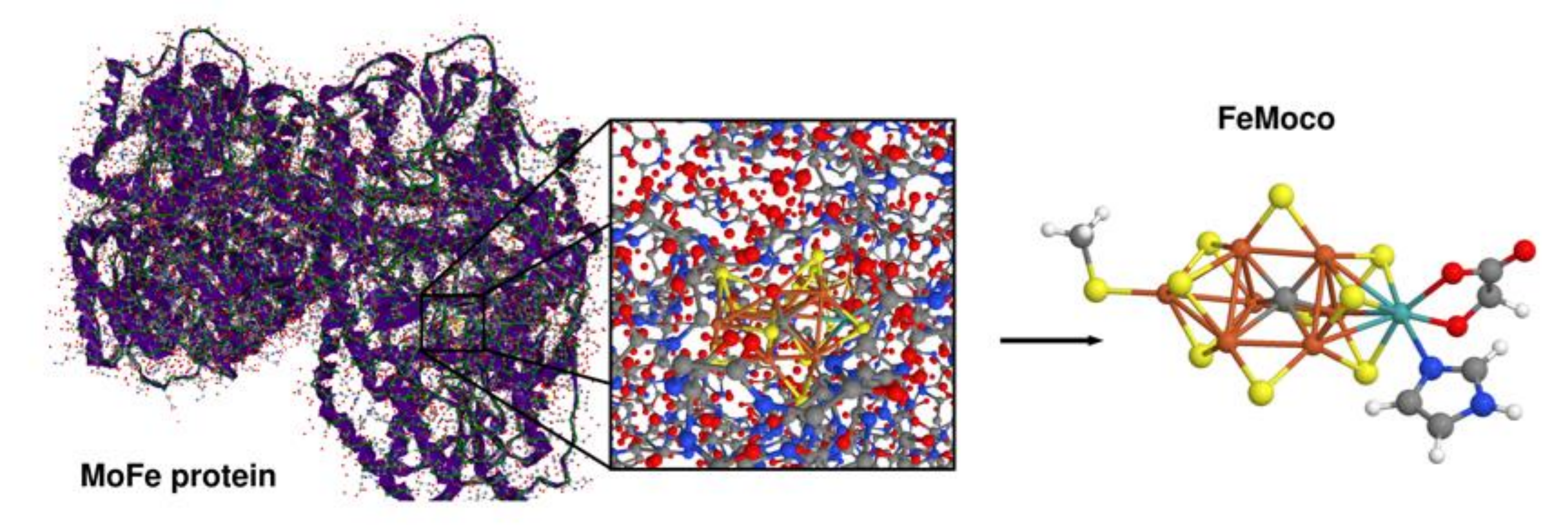


Image: CERN

Many problems are out of reach even for exascale supercomputers but doable on quantum computers.

Understanding biological Nitrogen fixation



Intractable on classical supercomputers

But a 200-qubit quantum computer will let us understand it

Finding the ground state of Ferredoxin Fe_2S_2

Used in reactions and energy transport in photosynthesis

Classical algorithm	Quantum algorithm 2012	Quantum algorithm 2015
!	~3000	~1
INTRACTABLE	YEARS	DAY

Research on quantum algorithms and software is essential!

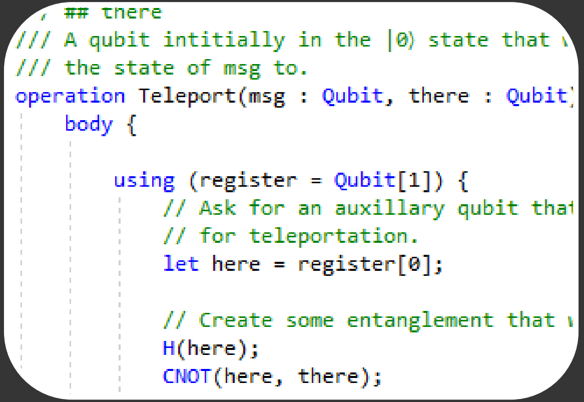
```
/// ## there
/// A qubit intitially in the |0⟩ state that w
/// the state of msg to.
operation Teleport(msg : Qubit, there : Qubit)
    body {

        using (register = Qubit[1]) {
            // Ask for an auxillary qubit that
            // for teleportation.
            let here = register[0];

            // Create some entanglement that w
            H(here);
            CNOT(here, there);
```

Quantum algorithm in high level language (Q#)

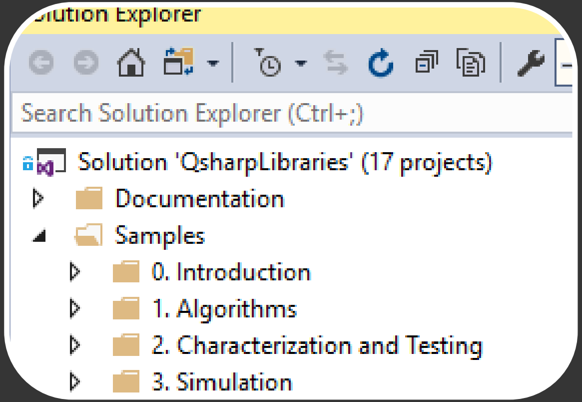
Compiler

Machine level instructions

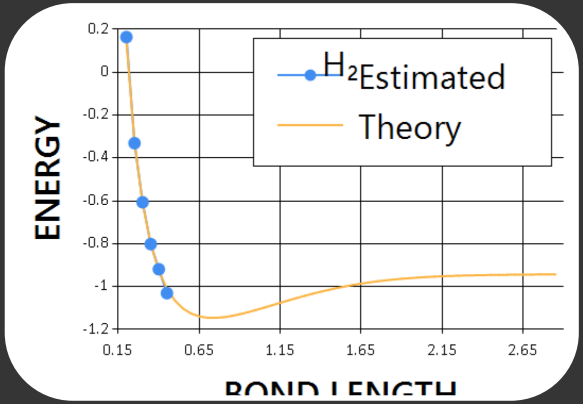
Microsoft Quantum Development Kit



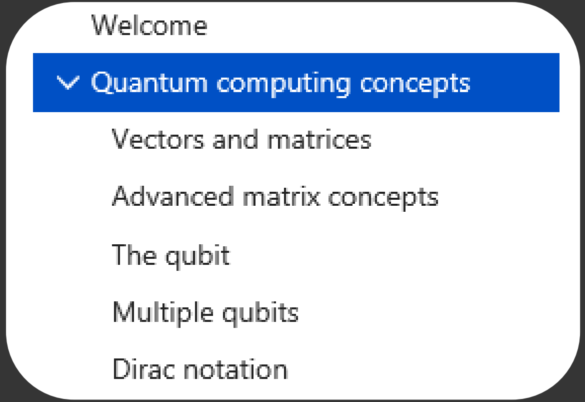
Quantum programming language



Visual Studio integration and debugging



Local and cloud quantum simulation



Extensive libraries, samples, and documentation

Developing quantum applications

1. Find quantum algorithm with quantum speedup

2. Confirm quantum speedup after implementing all oracles

3. Optimize code until runtime is short enough

4. Embed into specific hardware estimate runtime

Simulating Quantum Field Theories: Classically

Feynman diagrams

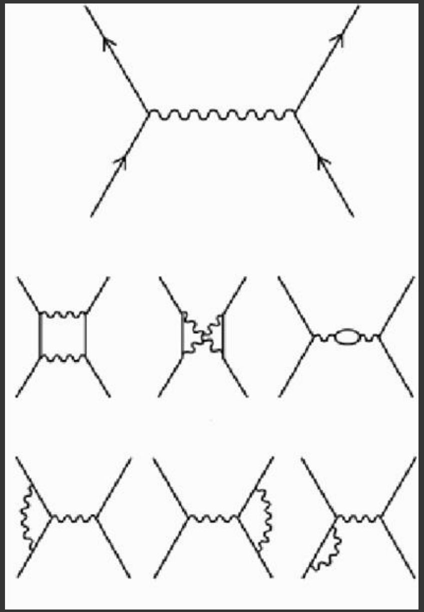


Image: Encyclopedia of Physics

Break down at strong coupling or high precision

Lattice methods

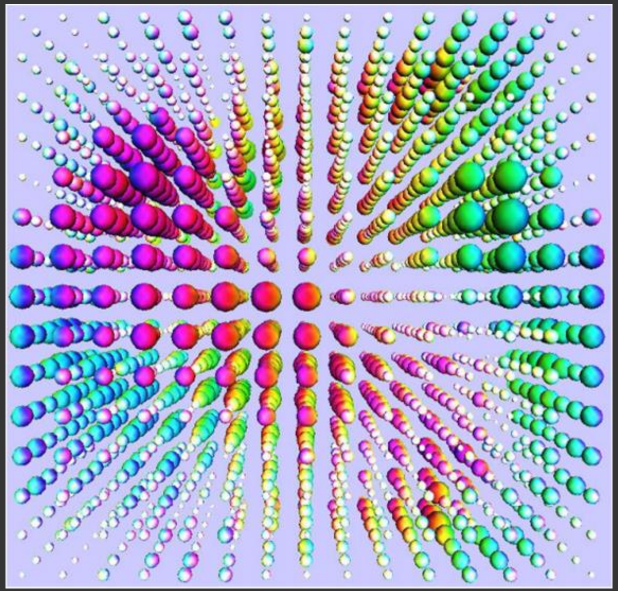


Image: R. Babich et al.

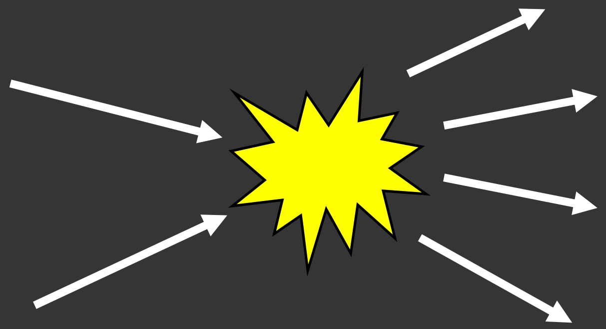
Good for binding energies.
Sign problem: real time dynamics, high fermion density.

There's room for exponential speedup by quantum computing.

A QFT Computational Problem

Input: a list of momenta of incoming particles.

Output: a list of momenta of outgoing particles.



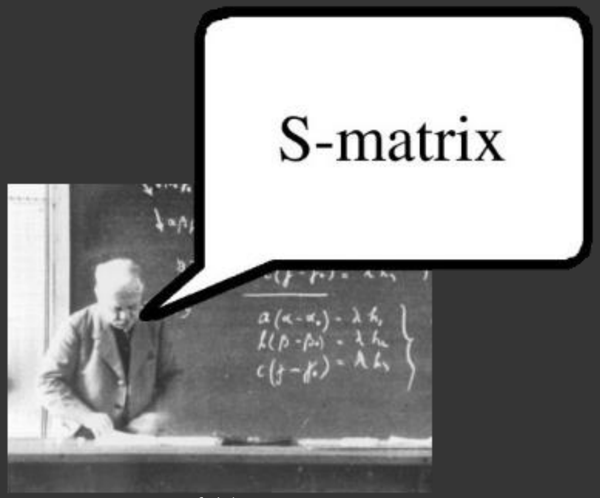


Image: Sommerfeld center

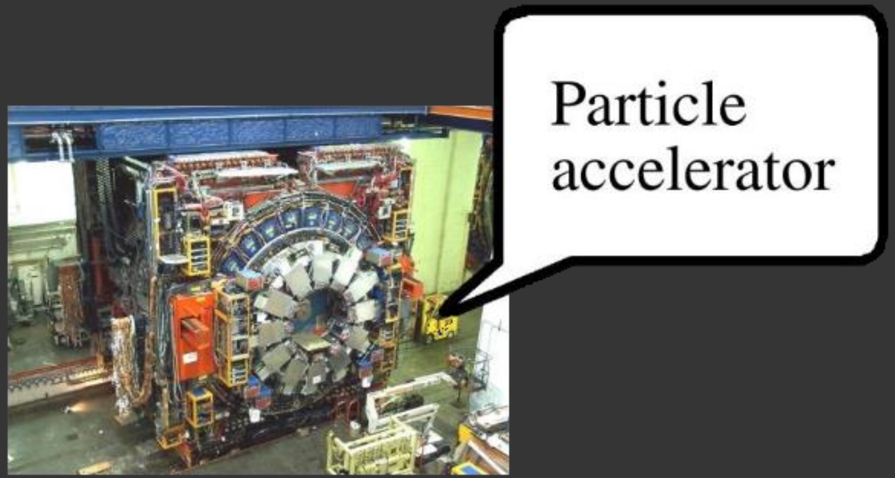
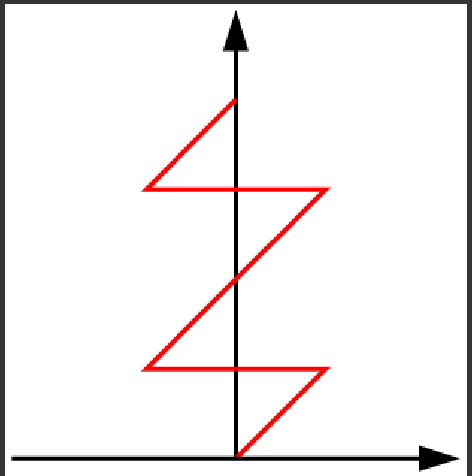


Image: Fermilab/wikimedia

Simulating Quantum Field Theories: Quantumly

Efficient simulation algorithms for example QFTs:

- Bosonic: Massive ϕ^4
  [Jordan, Lee, Preskill, *Science* 336:1130, 2012]
- Fermionic: Massive Gross-Neveu
  [Jordan, Lee, Preskill *ArXiv:1404.7115*, 2014]



Next steps:

- Improve efficiency and generality (simulate the standard model?)
- Implement in Q#. Get quantitative resource estimates.

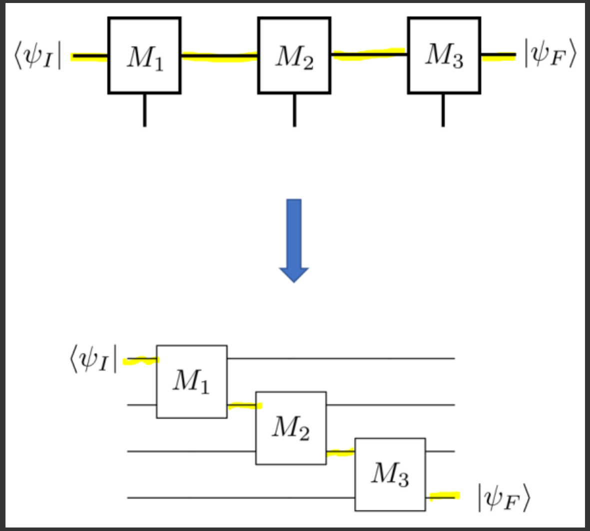


Image: Emilio Segre archives

What I’m trying to do is get you people who think about computer simulation to see if you can’t invent a different point of view than what the physicists have.

-Richard Feynman, 1981

Image: Wikimedia

In thinking and trying out ideas about “what is a field theory” I found it very helpful to demand that a correctly formulated field theory should be soluble by computer… It was clear, in the ‘60s, that no such computing power was available in practice.

-Kenneth Wilson, 1982

Solving Systems of Linear Equations

Harrow, Hassidim, Lloyd, Phys. Rev. Lett. 2009

Solve $A\vec{x} = \vec{b}$ in Log(N) time (in some cases).

Uses quantum algorithms to implement e^{-iAt}

Vast swaths of engineering are done by discretizing differential equations and solving the resulting linear equations.

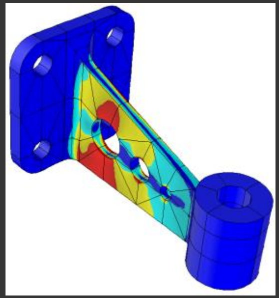


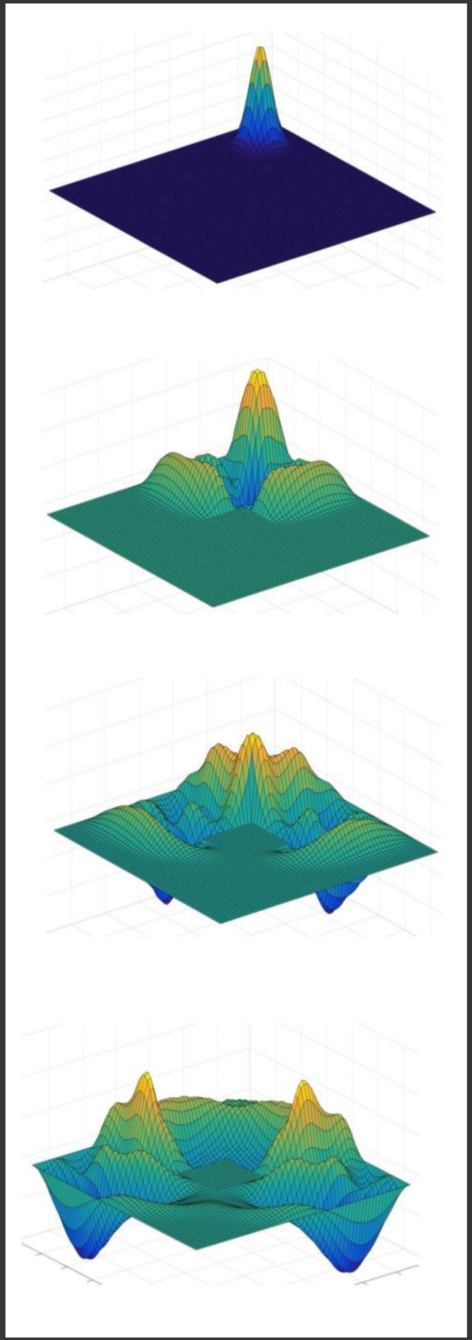
Image: Manil Suri

Is this a good application for quantum computers?

Solving wave equations

$$\frac{\partial^2 \phi}{\partial t^2} = \nabla^2 \phi$$

- Maxwell's equations
- Klein-Gordon equation
- Quantum computers have exponential memory savings and polynomial time savings.
  (Clader, Jacobs, Sprouse, *Phys. Rev. Lett.*, 2013)
  (Costa, Jordan, Ostrander, 2018)
- Constant factors need improvement!
  (Scherer et al., 2015)



Big quantum advantage, asymptotically

	quantum	classical
time	$T\dfrac{D^2}{h}$	$T\left(\dfrac{\ell}{h}\right)^D$
space	$D\log(\ell/h)$	$\left(\dfrac{\ell}{h}\right)^D$

h = lattice spacing

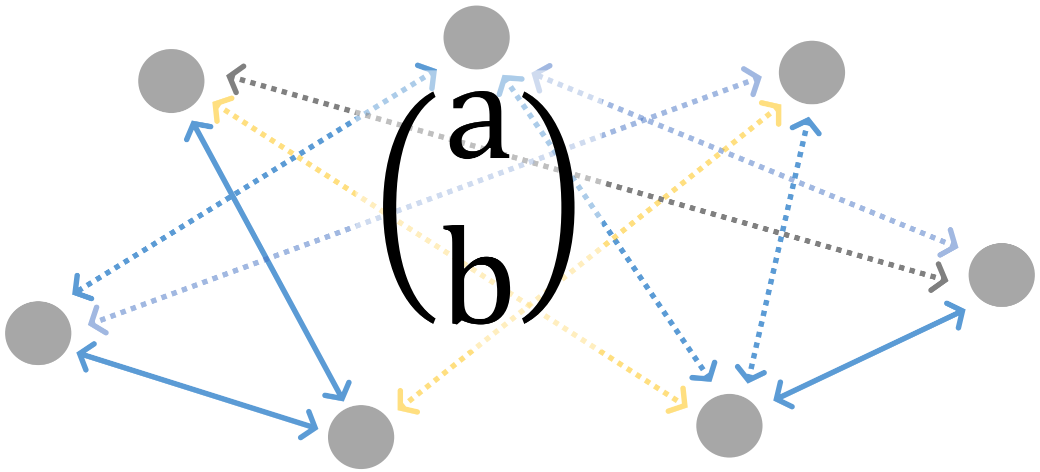
ℓ = diameter of region

D = # dimensions

T = duration of process

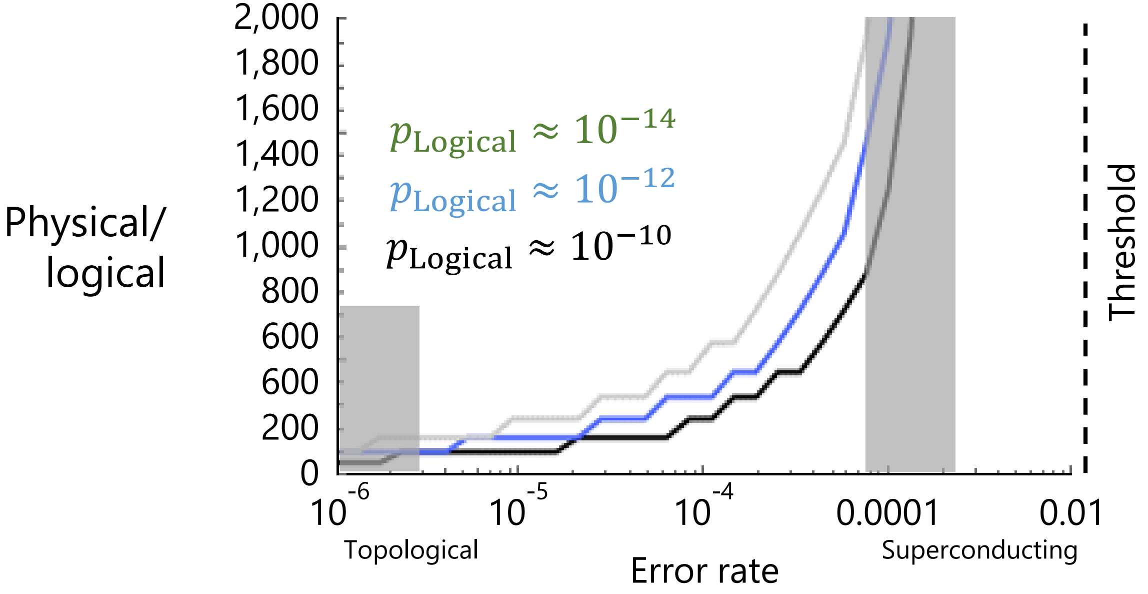
Quantum Error Correction

Information is stored redundantly in correlations between many small quantum systems. When one system is effected, the information is unharmed.



Error rate

is the probability that a qubit or operation fails within one quantum computing clock-cycle



Topological qubits

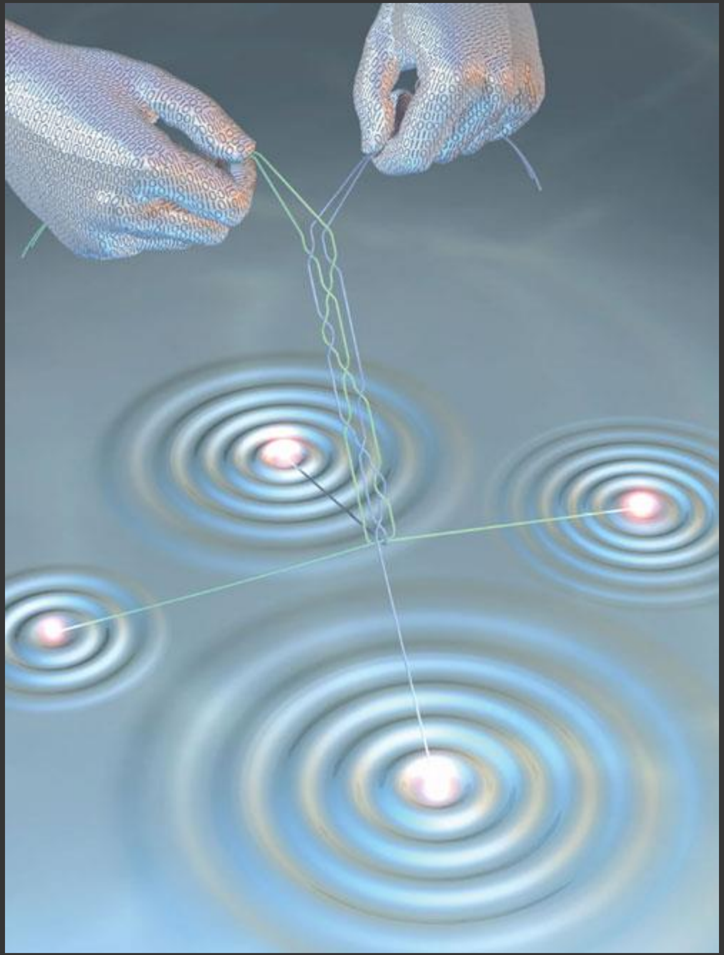


Image: Scientific American

- Topological quantum field theory was introduced in pure math and applied to quantum gravity.
- Later it found use describing exotic phases of matter at low temperature.
- Michael Freedman (Microsoft) and Alexei Kitaev (Caltech) realized these could form a robust substrate for quantum computing.

Putting topology to work.

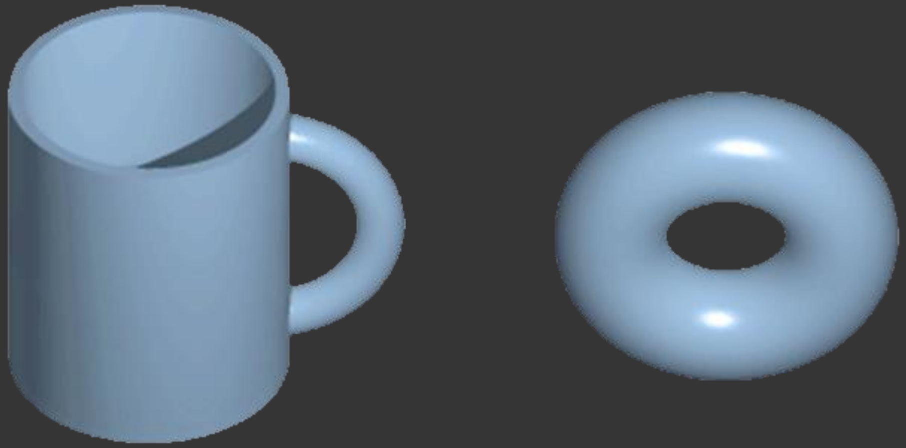


Image: Wikimedia

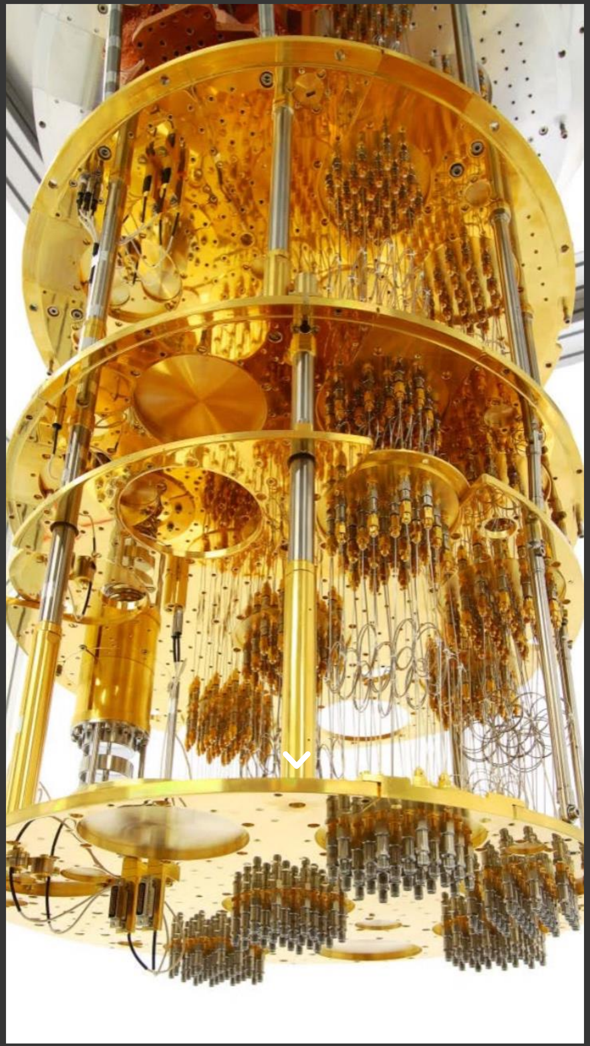
HOME SEARCH The New York Times

TECHNOLOGY

Microsoft Makes Bet Quantum Computing Is Next Breakthrough

By JOHN MARKOFF JUNE 23, 2014

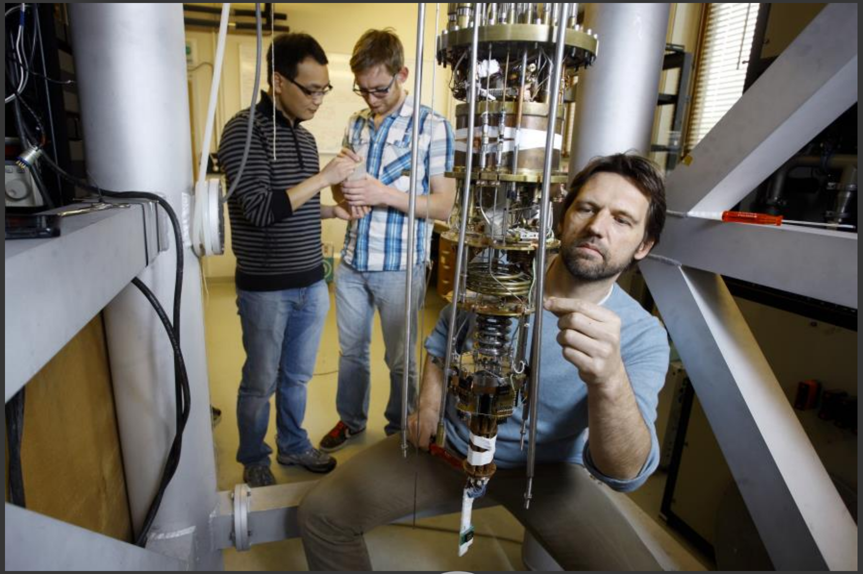
Topological qubits: Majorana version



- Microsoft is pursuing qubits built from Majorana fermions, which are excitations in a topological phase.
- The target error rate is 10^{-6}
- No other qubit under development has clear prospect to surpass 10^{-3}
- Orders of magnitude lower overhead.

"MAJORANA PARTICLE GLIMPSED IN LAB."

BBC NEWS

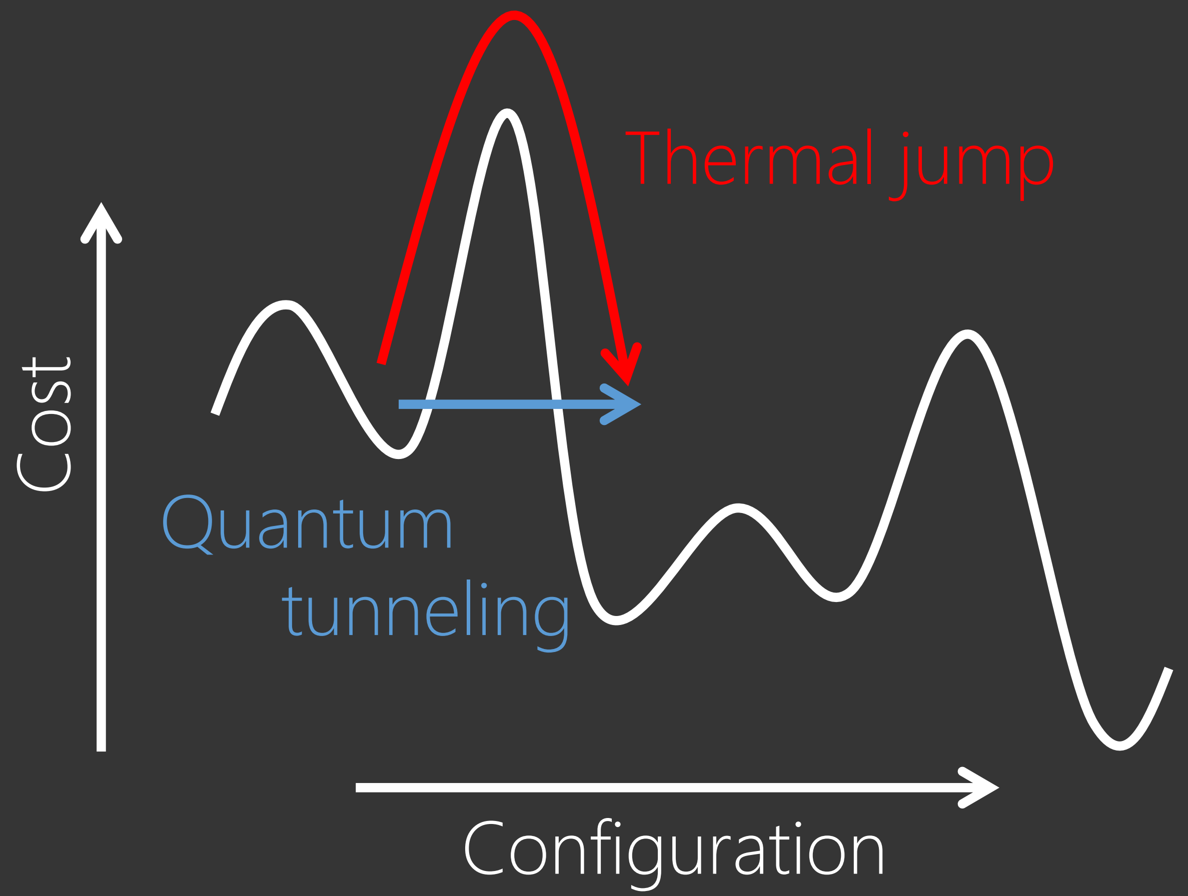


2012

Quantum-Inspired Optimization

- In certain cases, quantum tunneling can escape from local minima that trap conventional methods such as simulated annealing.

- Serendipitous discovery ~2015: Monte Carlo simulation of quantum tunneling can be very successful optimizer.

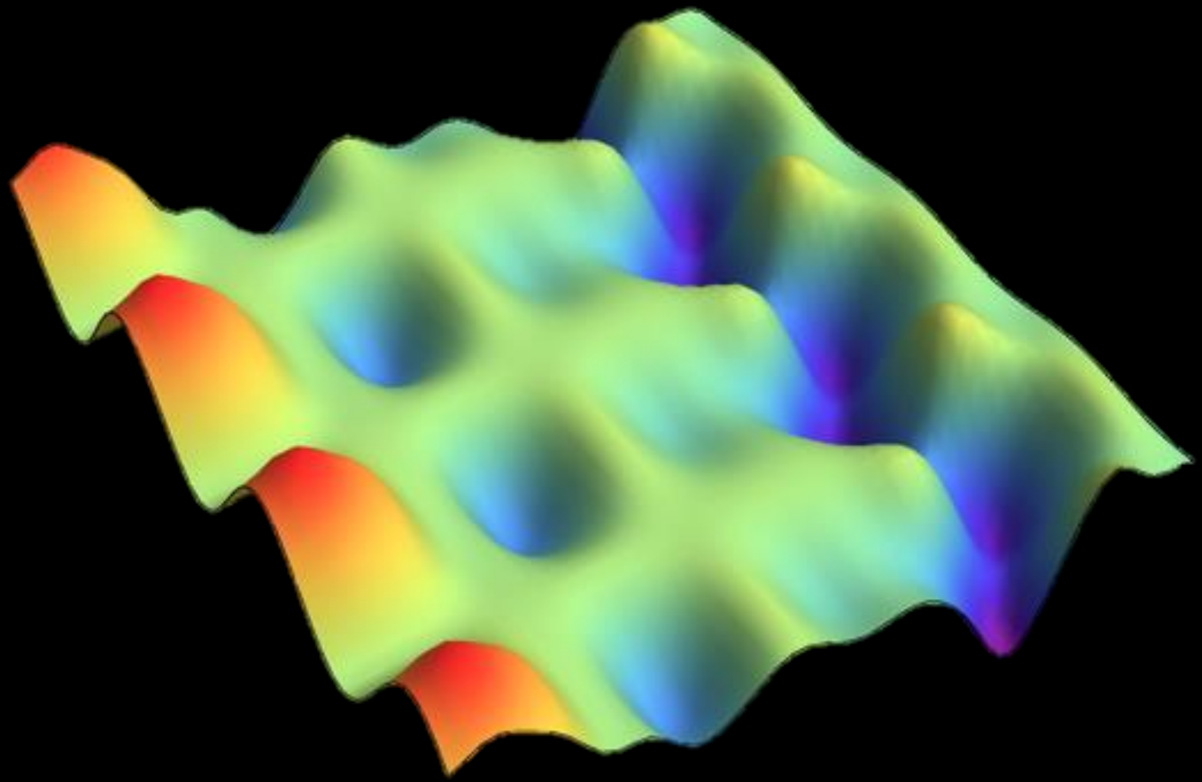


QIO Case Study: MAXSAT

Solver	#Ins.	borealis	SC2016	Swcca-ms	CCLS	CnC-LS	SsMonteCarlo	CCEHC	Ramp	dsat-wpm3-s-in-ms	dsat-wpm3-in-ms	HS-Greedy	Naps-1.02-ms	Optiriss6-in	WPM3-2015-in
ndom/abrame-habet/max2sat/120v	45	2.09(45)	1.98(45)	2.06(45)	1.50(45)	2.28(45)	1.32(45)	3.05(45)	1.74(45)	15.80(45)	6.16(45)	2.46(17)	0.00(0)	0.00(0)	0.00(0)
ndom/abrame-habet/max2sat/140v	45	2.45(45)	2.23(45)	2.61(45)	2.35(45)	2.56(45)	1.73(45)	2.97(45)	1.97(45)	16.43(45)	6.25(45)	2.81(14)	0.00(0)	0.00(0)	0.00(0)
ndom/abrame-habet/max2sat/160v	45	2.84(45)	2.45(45)	3.05(45)	2.85(45)	2.94(45)	3.06(45)	3.48(45)	2.76(45)	16.22(45)	6.36(45)	3.18(18)	0.00(0)	0.00(0)	0.00(0)
ndom/abrame-habet/max2sat/180v	44	2.91(44)	3.16(44)	2.90(44)	3.09(44)	3.02(44)	3.38(44)	3.86(44)	3.46(44)	16.64(44)	6.29(44)	3.72(23)	0.00(0)	0.00(0)	0.00(0)
ndom/abrame-habet/max2sat/200v	49	3.20(49)	3.14(49)	3.33(49)	4.05(49)	2.76(49)	3.32(49)	4.04(49)	3.35(49)	16.47(49)	6.28(49)	3.96(18)	0.00(0)	0.00(0)	0.00(0)
ndom/abrame-habet/max3sat/110v	50	1.52(50)	1.77(50)	1.83(50)	1.85(50)	1.23(50)	2.06(50)	3.33(50)	1.75(50)	17.54(48)	6.45(50)	1.73(1)	0.00(0)	0.00(0)	0.00(0)
andom/abrame-habet/max3sat/70v	45	1.18(45)	1.44(45)	1.12(45)	1.40(45)	1.19(45)	1.55(45)	1.99(45)	1.28(45)	15.89(45)	6.30(45)	1.22(7)	0.00(0)	0.00(0)	0.00(0)
andom/abrame-habet/max3sat/90v	49	1.37(49)	1.65(49)	1.50(49)	1.76(49)	1.35(49)	1.81(49)	3.30(49)	1.66(49)	16.47(49)	6.33(49)	1.65(7)	0.00(0)	0.00(0)	0.00(0)
highgirth/3sat	50	3.31(50)	3.23(50)	3.44(50)	7.09(50)	1.39(50)	44.76(49)	26.09(43)	34.94(43)	108.94(15)	51.95(10)	0.00(0)	0.00(0)	0.00(0)	0.00(0)
highgirth/4sat	32	1.93(32)	1.70(32)	1.89(32)	8.51(32)	1.49(31)	32.24(29)	27.37(18)	14.62(15)	50.13(19)	35.99(19)	0.00(0)	0.00(0)	0.00(0)	0.00(0)
Total	454	454	454	454	454	453	450	433	430	404	401	105	0	0	0

- MAXSAT is probably the second most widely studied discrete optimization problem after travelling-salesman. (Over 9000 journal papers.)
- A contest for the best MAXSAT solver on benchmarking instances has been run each year since 2009.
- Katzgraber's QIO method wins random unweighted category at MAXSAT 2016.

Thanks



Quantum-inspired answers today

Quantum answers tomorrow